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The potential of cassava biomass and applicable technologies for sustainable biogas production in South Africa: A review

Vincent Okudoh [a,*], Cristina Trois [b], Tilahun Workneh [b], Stefan Schmidt [c]

[a] Faculty of Applied Sciences, Cape Peninsula University of Technology, Cape Town, South Africa
[b] School of Engineering, University of KwaZulu-Natal, Durban, South Africa
[c] Discipline of Microbiology, School of Life Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa

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ABSTRACT

Bioenergy production from agricultural crop biomass or residues is gaining interest due to the escalating cost of fossil fuels and the need to mitigate global warming caused by increasing GHG emissions. Of all the different feed stocks used for bioenergy production in Africa, cassava biomass potentially offers multiple benefits for producing biofuels such as biogas. This critical review on cassava intends to highlight the bioenergy (biogas) potential of the crop in Africa. Initially, the basic agricultural properties of cassava will be reviewed. Cassava contains large amounts of fermentable sugars. Its starch content ranges from 20 to 35% based on fresh and at about 80.6% based on dry weight with 38.6% total dry matter. It has the highest yield of carbohydrates per hectare with the exception of sugarcane and sugar beet. It thrives well in all ecological zones with one of the best water-footprints especially on relatively low fertility soils, in drought conditions and requires low agrochemical input. High yielding and disease resistant cassava varieties have been developed for both food and non-food applications with China adopting the crop to meet its 2020 biofuel target. Based on the available literature, various pretreatment techniques including mechanical, chemical, thermal, ultrasonic and wet explosion strategies were considered. The advantages and disadvantages of each technology as well as adoptable technologies for cassava biogas production and its optimization in Africa and especially South Africa will be critically discussed. This review highlights the highly politicized food vs energy debate as the most relevant bottleneck for using "potential" food (like cassava and other energy crops) for energy production. It suggests a paradigm shift and a more holistic and complementary view of food and biomass energy production. In conclusion, it recommend considering cassava and its biomass as the next energy crop for biogas production in Africa and especially South Africa.

Contents

* Corresponding author. Tel.: +27 214603507.
E-mail address: okudohv@cput.ac.za (V. Okudoh).

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1. Introduction

The key issues faced by many developed and developing countries of the world today are mainly future energy security and better use of natural resources. A look at the African continent in terms of energy production and consumption shows the inequality in the distribution of fossil fuels. About 70% of the countries in Africa rely on imported energy. This situation is aggravated by huge unemployment and low gross domestic product (GDP). According to a recent report by the Food and Agriculture Organization (FAO) in 2013, Africa has the lowest overall GDP ($1629.5 billion) in the world, eight times less than Asia, five times less than Latin America and 26 times less than developed economies. GDP per capita in Africa was $1623.6 in 2010, two times less than Asia, five times less than Latin America and 21 times less than the per capita GDP of developed economies. GDP growth in 2010 was exceeding 6% only for Nigeria, Botswana and some East and Central African countries but was less than 3% for South Africa and Angola. A huge chunk of African countries' national budget which could have gone into development is spent on energy imports. Moreover, limited availability and lack of access to energy remains one of the most important factors affecting industrial development (i.e. agriculture, mining and tourism) in the continent. This leads to in-fighting (wars), violent service delivery protests, poor infrastructural development and spread of lethal diseases.

The above scenario supports the call for urgent development of renewable energy (RE) resources and in particular bioenergy. The bioenergy potential by 2050 on unutilized land for sub-Saharan Africa is estimated to be 317 Exajoules (EJ) per year [1]. This figure is higher than most other regions of the world. For example, only about 20% of South Africa's total land mass of 120 million hectares (Mha) is currently used for biomass production [2]. Conversion of biomass to energy will help reduce the dependence on fossil fuels as well as mitigate the negative social and environmental impacts such as rural unemployment and global warming [3].

Of all the different biofuels, biogas currently presents the most opportunities to the rural population in Africa while it is a major low-carbon fuel source. In addition, to the national governments in Africa, it offers multiple-benefits such as:

- Foreign exchange savings for non-oil producing countries.
- Boost for rural farming and economy through job creation and income gains.
- Beneficial use of organic agricultural and municipal solid waste (MSW) for energy production.
- Improved environmental quality through CO_2 emission reduction [4].

The use of cassava provides huge potential for bioenergy production and in particular biogas with several advantages. According to a report by the Forum for Agricultural Research in Africa (FARA) in 2010, there are thousands of acres of degraded and unutilized land in Africa where crops like cassava can be produced for biofuels on a large scale without damage to food production or natural habitats [5]. The advantage that cassava has over many other crops is that it can thrive in areas where the land has been degraded and has the highest yield of carbohydrates (4.742 kg/carb) per hectare with the exception of sugarcane and sugar beet [6]. It thrives very well on soils of relatively low fertility where the cultivation of other crops will be uneconomical [7]. It also has the ability to thrive in drought conditions and requires low input of agro-chemicals [8]. Cassava contains large amounts of starch (20–35% fresh and 80.6% dry weight) [9,10] and total dry matter (38.6%) [11], and has been reported to have the smallest water-footprint (21 m^3/GJ) compared to all other crops [12]. Based on the above reasons, cassava has recently gained considerable attention for the production of bioenergy [10] and in particular for the production of biogas [13–17].

Biogas from biomass is one of the best sources of renewable energy because it can be used for heating, as a fuel or natural gas equivalent and can be converted to electricity. In Germany, for example, the number of biogas plants has exceeded 7000 units in 2011 with electrical capacity already exceeding 2.8 GW [18,19]. The production of biogas from cassava biomass is a biochemical process that takes place through the anaerobic food chain involving mainly prokaryotes [20,21]. The major constituents of biogas are methane (CH_4) and carbon dioxide (CO_2). Trace amounts of H_2S, NH_3, H_2, N_2 are also present [22]. Methane is the most valuable component of biogas and typically accounts for more than 60%. Biogas is considered to be a valuable fuel [23,24] with the calorific value ranging from 5000 to 7000 kcal/m^3 depending on the concentration of CH_4 in it. For comparison, one cubic meter of biogas containing about

60% methane is equal to 0.7 m^3 of natural gas, 0.7 kg of fuel oil, 0.6 kg of kerosene, 0.4 kg of petrol, 3.5 kg of wood, 12 kg of manure briquettes, 4 kWh of electrical energy, 0.5 kg of carbon and 0.43 kg of butane [25]. Biogas production employs various types of feedstock. However, the quality and yield of the biogas produced depends on the composition of the feedstock used [26,27].

Traditionally, biogas studies were biased towards soluble substrates such as present in industrial wastewaters [28] and only recently increasing numbers of studies focused on energy crops such as fodder beet or cassava. High yielding and disease resistant cassava varieties are now developed for both food and non-food applications [29,30]. Whilst cassava has had a long history in Africa, it is not a well-known crop in South Africa [31]. Very few studies were carried out in the 1980s for the purpose of starch production [32,33] and since then not much has improved.

Therefore, the objective of this review is to renew interest in cassava and argue for its adoption for bioenergy production in Africa, and especially so in South Africa. The first section will deal with the nature of cassava and its importance while the second section will scope and evaluate the potential of cassava biomass for bioenergy production. The third section will look at existing biogas production technologies and critically evaluate factors that influence its production and approaches to optimize cassava biogas yields. The discussion and conclusions attempt to argue for cassava biomass adoption for sustainable bioenergy in Africa, especially in a developing economy like South Africa.

2. Cassava and its characteristics

2.1. What is cassava?

Cassava (*Manihot esculenta* Crantz), synonyms: manioc, yucca, tapioca, is a tubercle 5 to10 cm in diameter and 15 to 35 cm in length (Fig. 1). It is produced in almost all mild and tropical countries and grows in degraded soils where almost nothing else can grow [7]. It does not need fertilizers, insecticides, or additional water. Furthermore, cassava can be harvested any time between 8 to 24 months after planting [34]. Native to South America cassava has historically been a human and animal feed source, and currently has many industrial applications [34]. Based on its hydrocyanic acid content, it is categorized into sweet cassava (directly consumed) and bitter cassava for making starch and other industrial purposes [35].

2.2. Composition of cassava

Cassava tuber is organically rich in starch and carbohydrates but contains small amounts of protein, vitamins and minerals [36]. The starch content of fresh cassava tuber was reported as 32.4% while the dry cassava contained 80.6% [37]. The protein contents of fresh and dry cassava were also reported as 1% and 1.41%, respectively (Table 1). Soccol [38] reported that fresh cassava tubers had 65% of moisture, 0.9% of ash and 0.03% of phosphorus.

2.3. Cassava cultivation

Cassava crop is very resilient and can be cultivated in a wide variety of agro ecological zones. It is normally propagated by cut stems [34] and can thrive in marginal environments where crops such as maize, yam, plantain, banana, sorghum, millet and others cannot survive. It is probably the only crop that can survive in all ecological zones [40] making it ideal for poor farmers to cultivate. Another advantage is that it produces higher yields per hectare of land than other crop in its category such as maize, yam, rice and wheat. It is one of the most efficient producers of starch and carbohydrates among all crops [39].

Recently, African governments and international non-governmental organizations such as the United Nations International Children's Emergency Fund (UNICEF), the International Fund for Agricultural Development (IFAD), and the International Centre for Tropical Agriculture (CIAT) have become fully involved in the multiplication and distribution of cassava in order to harness the huge potential of this crop for food and non-food applications [30].

Table 1
Physical and chemical composition of cassava tubers (100 g).

Composition	Unit	Fresh weight	Dry weight	References
Calories		135	335	[36]
Peel	%	10–20	ND	[7]
Cork layer	%	0.5–2.0	ND	[7]
Edible portion	%	80–90	ND	[7]
Moisture	%	62–66	15-19	[36–38][a]
Total solids (TS)	%	38	81	[38]
Volatile solids (VS)	%	99	98	[38]
Protein	g	1	1	[7,37]
Total nitrogen	%	0.22	0.46	[38]
Lipid	g	0.20	0.50	[36]
Starch	g	18–32	81	[36,38]
Fibre	g	1.10	1.20	[36]
Carbohydrate	%	35	ND	[7]
Total carbon (TC)	%	19	40	[38]
Ash	g	0.9–1	2	[7,37,38]
Calcium	mg	26	96	[36]
Phosphorus	mg	32	81	[36]
Iron	mg	1	8	[36]
Sodium	mg	2	ND	[36]
Potassium	mg	394	ND	[36]
Vitamin B2	mg	0.04	0.06	[36]
Vitamin C	mg	34	0.00	[39]
Niacin	mg	0.60	0.80	[36]
Cyanide	%	ND	2	[36]

ND = not determined.

[a] Figures based on cassava variety KU50 from Makhon Ratchasima province of Thailand.

Fig. 1. Cassava tubers: (A) with stems attached; (B) without stems [7,57].

Whilst some cassava cultivation trials have been carried out in South Africa in the Eastern Cape [33] and areas of KwaZulu-Natal [32] in the 1980s, they were focused mainly on starch production. The successes achieved were limited mainly due to disease infestation caused by the Leaf Mosaic virus and bacterial blight. However, both diseases have been controlled by the International Institute of Tropical Agriculture (IITA) through genetic breeding and introduction of resistance genes into high yielding cassava varieties. Varieties that yield five times more tubers per hectare than the traditional cultivars have been established [30].

2.4. Cassava water-footprint

The water footprint (WF) of a crop is defined as the volume of freshwater used for its production at a particular area [41]. Water use in crop life cycles is dominated by the agricultural production stage. Normally, water footprints are classified into three categories; blue, green and grey WFs [41]. The green WF is used to describe the rain water evaporated during production and growth of the crop while the blue WF refers to the surface and groundwater evaporated during the growth of the crop. The volume of water that becomes polluted during crop production is called the grey WF which is normally discharged into the surrounding natural water system [12].

Table 2 shows the weighted global average of green and blue WFs for 13 established biofuel crops. It indicates that sugar beet is the best crop overall with the lowest WF and sorghum is the worst with the highest WF. The three oil crops viz., soybean, rapeseed and Jatropha are excluded from this conclusion due to minimal water content of seeds used [12]. On a global average, the blue WF is the most crucial for bioenergy crops. As shown in Table 2, cassava has the lowest blue WF compared to all other crops followed by sugar beet, potato, maize and sugarcane. Sorghum is the worst bioenergy crop judging from its blue WF [12].

2.5. Cassava production and trade

World cassava production is around 263 million tons (Mt) per year with Africa accounting for about 57% (~150 Mt) of the supply [42] in 2012 (Fig. 2A and B). Asia is second with 30.7%, while Latin America and the Caribbean are third with 12.2%. Nigeria is the largest producer of cassava in the world with more than 54 Mt at the end of 2012. Whilst Africa and Asia grew their share of cassava production in 2012, the Americas dropped from about 19% in 2010 to 12% in 2012. The Democratic Republic of Congo (DRC) with 16 Mt is the second largest producer of cassava in Africa after Nigeria in 2012 [42].

Table 2
Total weighted-global average water-footprint for 13 biofuel crops (m^3/GJ).

Crop	Total WF	Blue WF	Green WF
Sugar beet	46	27	19
Maize	50	20	30
Sugar cane	50	27	23
Barley	70	39	31
Rye	77	36	42
Paddy rice	85	31	54
Wheat	93	54	39
Potato	105	47	58
Cassava	148	**21**	127
Soya bean	173	95	78
Sorghum	180	78	102
Rapeseed	383	229	154
Jatropha	396	231	165

It is assumed that total biomass yields is used for electricity generation; average figures for 5 countries (India, Indonesia, Nicaragua, Brazil and Guatemala) [12].

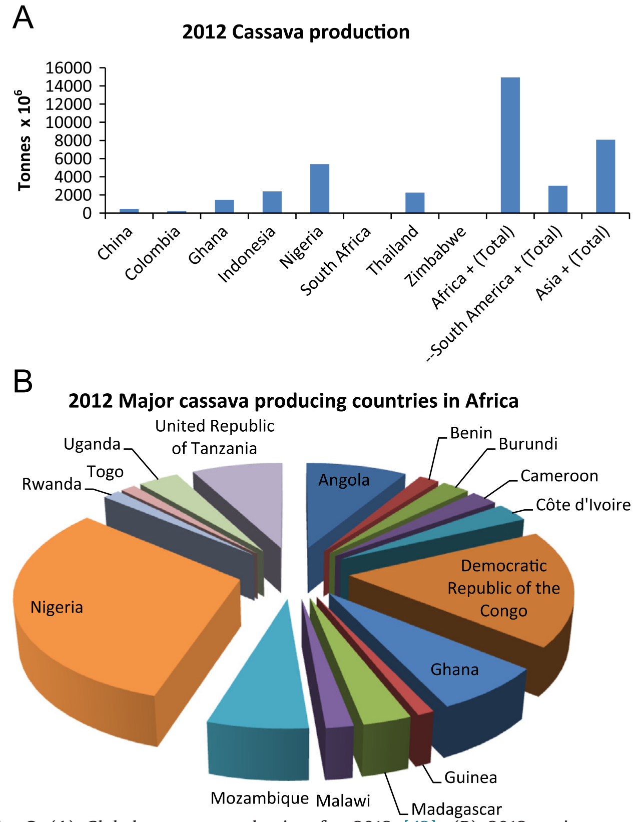

Fig. 2. (A) Global cassava production for 2012 [42]; (B) 2012 major cassava producing countries in Africa [42].

Whilst most of the cassava produced in Africa is used for food, Asia promotes the development of the crop for energy and industry. For example, in the People's Republic of China (PRC), cassava has been officially designated a major crop to meet their 2020 biofuel target [43]. Thailand and Indonesia are the largest Asian producers with 25 Mt and 22 Mt tons respectively in 2010. However, Indonesia (24 Mt) has overtaken Thailand (23 Mt) as the second largest producer in the world in 2012. China and Vietnam have increased their cassava production since 2008 and both produce between 8 and 9 million tons a year respectively. India's production has increased by about 30% since 2006. In fact, India delivered the highest yield of cassava with about 364 thousand hectogram per hectare (Hg/ha) in 2012 followed by Cook Islands (263 Hg/ha) and Taiwan (242 Hg/ha). Cassava production is relatively stable in Latin America and the Caribbean countries. Brazil is by far the largest producer in Latin America with 70% of the regional production with 24 Mt in 2012, thereby competing with Indonesia for second position in global production. Other minor producers are Colombia and Paraguay. In Colombia, for example, cassava production at huge scale is been promoted by the national government [44]. Fig. 2A and B clearly indicate zero production for South Africa. In the SADC (Southern African Development Community), apart from DRC the main countries producing cassava include Angola (10.6 Mt), Malawi (4.7 Mt), Madagascar (3.5 Mt), Zambia (1.3 Mt) and Zimbabwe with just above 228 thousand tons at the end of 2012 [42].

The world trade in cassava amounted to approximately 8 billion US dollars in 2010 [42], and revolves around the export and import of dried cassava and its starch. Although Nigeria is the largest producer of cassava in the world, it and the rest of Africa play a negligible role in the world cassava trade. African governments have paid little attention to the potentials of cassava until recently. The major cassava-exporting countries are Thailand, Indonesia, China and Vietnam. Thailand alone accounted for about 94% of the

global total export of cassava products in 2010 [42]. The major cassava product importing countries are member states of the European Union, China, South Korea, Indonesia and the United States. In 2000 the EU imported 6.9 million tons of cassava products alone [45].

The volume of world trade in cassava increases annually by about 36%. Despite the increased volume of the trade, the international market prices of cassava remain among the lowest compared to other crops in its category since the 1990s. The importers from EU countries control the world price. Since 2008 the price of cassava roots ranged from about 57.2 US dollars/ton to $ 41.4 in 2009 and $ 76.1 in 2010 with Thailand having the lowest price for its exports [46].

2.6. Cassava consumption and utilization

Global demand for cassava by-products is on the increase as the world leaders in cassava production, Nigeria, Brazil and Thailand, undergo transformation towards industrial uses of cassava [47]. Current data on consumption is scarce, however in 2001, it was estimated that 84% of the cassava produced in Nigeria was used as food for human consumption; out of this 70% was processed into 'gari' and the remaining 14% into other human food products such as 'lafun' (fermented cassava flour), 'fufu/akpu', abacha and tapioca. In a 2004 study conducted by the Nigerian Federal Ministry of Health, the per capita consumption per day of cassava as human food was 240 g, 221 g and 214 g for rural, medium and urban dwellers, respectively [45].

In Brazil, 70% to 80% of cassava produced is used exclusively for making flour. Cassava starch is used in many sectors, including the food industry, pharmaceutical industry, foundry, textiles, paper and adhesives. According to the FAO [42], African countries have little or no presence in the industrial processing of cassava starch, apart from Nigeria and South Africa while Thailand processes most of its cassava for export. The continent consumes the roots fresh or after the first stage in their processing. Estimates of industrial use suggest that approximately 16% of cassava root production was utilized as an industrial raw material in 2001 in Nigeria. About 10% of this was used as cassava chips in animal feeds, 5% was used for syrup concentrate for soft drinks and 1% went into high quality cassava flour for baking and confectioneries, dextrin pre-gelled starch for adhesives, starch and hydrolysates for pharmaceuticals, and seasonings [48].

To date cassava remains, to most Africans, a food security or a self-sufficiency crop. It is not thought of as an agro-food industry capable of moving the African economy forward with the potential to provide the following:

(i) A marketable convenience food for the growing urban market.
(ii) An export-earning potential crop.
(iii) A high quality flour, starch and animal feed source.
(iv) A renewable energy source in the form of biofuels (ethanol and biogas).

These are some of the knowledge gaps, attitudes and mind-sets that need to be changed in order to stimulate cassava's role and importance in Africa's economic development [47].

In South Africa, no official data on production and consumption of cassava is available [42] (see Fig. 2). The reason is because cassava is not yet a staple food in the country and the small scale production reported in the Eastern Cape and KwaZulu-Natal regions is primarily for starch and animal feed. In South Africa, maize is the chief staple food and the nation's chief farm export as well as sugarcane, wheat, potatoes and grapes. With the exception of rural areas, it appears that since South Africa is a net food exporter, food security in view of cassava is not a major problem in urban areas [42]. This shows that in principle cassava can be produced for bioenergy production in South Africa, given the agro-climatic conditions in the country which are suitable for its production.

Whilst cassava biomass is still a small player on the biofuel arena, its role as energy crop should increase considering the direction taken by China. With one ton of fresh cassava assuming 30% starch content and 80% fermentable sugars present in the dry material about 280 l of 96% ethanol can be produced [49]. Biogas production from cassava biomass is still in its infancy in Africa although the industrial potential of this crop gains momentum in Africa and especially so in South Africa.

3. Cassava bioenergy potential

There are three potential biofuels that can be generated at an industrial scale from cassava biomass viz., bioethanol, biodiesel and biogas.

3.1. Bioethanol

Most countries with large potential for growing cassava such as Nigeria, Benin, Mozambique, Ghana, Indonesia and Thailand already use cassava for industrial purposes. Bioethanol initiatives have been identified in these countries and current production is approximately 100,000 t of cassava ethanol per year. This figure could rise to 2 Mt if ambitious plans by China and other developing countries like Nigeria and South Africa are implemented. On a global scale 6×10^6 t of cassava ethanol could be produced per year [7].

The technology for producing ethanol from cassava is very well-developed. Cassava is performing well on all processing steps. A study by Wang [9] compared the yields of bioethanol from different energy crops (Table 3) and showed that cassava compared favourably to other crops such as maize, sugarcane and sweet sorghum. In fact, cassava had the highest annual yield of bioethanol (up to 6 t/ha) than any other crop including sugarcane (Table 3) [9].

A study by Nuwamanya et al. [11] using non-edible parts of cassava for bioethanol production revealed that cassava peels and stems contains greater than 28% dry matter. The study showed that 10 g cassava biomass yielded > 8.5 g sugar, which in turn produced $> 60\%$ bioethanol based on the amount of ethanol produced from each 500 mL batch of the fermentation solution (beer).

Rattanachomsri et al. [50] produced 14.3 g/L of ethanol from 4% cassava pulp by first using multi-enzyme from *Aspergillus niger* strain BCC17849 for pretreatment before fermenting with *Candida tropicalis*. The crude multi-enzyme composed of non-starch polysaccharide hydrolysing enzyme activities, including cellulose, pectinase and hemicellulose resulting in high yield (716 mg/glucose and 67 mg/xylose) of fermentable sugars. A summary of some previous studies carried out on cassava for bioethanol production is shown in Table 4.

Table 3
Comparison of bioethanol production from different energy crops.

Crops	Yield (T ha $^{-1}$ year $^{-1}$)	Conversion rate to ethanol (L T)	Bioethanol yield (L ha $^{-1}$ year $^{-1}$)
Sugar cane	70	70	4900
Sweet sorghum	35	80	2800
Rice	5	450	2250
Maize	5	410	2050
Wheat	4	390	1560
Cassava	40	150	6000

Adapted from [9,10]; L, litres; T, tonnes; ha, hectares.

Table 4
Some previous bioethanol studies on cassava and its products.

Feedstock	Method	Bioethanol yield	Refs.
Cassava peels, stems, leaves and roots	Sugar fermentation; distillation; *Saccharomyces cerevisiae*	> 60% per 8.5 g of sugar	[11]
Cassava starch and chips	Batch (1 L); mesophilic; *Clostridium saccharoperbutylacetonicum* N1-4	21 g/L of sample; 63% (w/v) higher than maize	[50]
Cassava pulp	Enzyme saccharification with *Aspergillus niger* BCC17849; fermentation with *Candida tropicalis*	14.3 g/L per 4% (w/v) pulp	[45]
Cassava slurry	Ultrasonic pretreatment	43.05 g/L sample; 95.72% fermentation efficiency; three times higher yield than control	[16]
Cassava waste	Enzyme; acid hydrolysis; 10 L fermenter; *Saccharomyces cerevisiae TISTR 5596*	3.62 g/L; 91% (w/v) theoretical yield	[51]

Table 5
Biogas studies involving cassava and its products.

Substrate	Method	Biogas yield ($m^3\ kg^{-1}$ VS)	Highest Methane content	Refs.
Dried Cassava tubers, cow dung (seed culture) and mud	Continuous two-phase digesters; 6 L acid tank; 21 L methane tank; mesophilic	13.2 L per kg VS	64%	[52]
Cassava roots (100 g/L) and chicken manure	Single-stage batch digester; mesophilic; urea (0.4 gL^{-1}); scaled up to 50 L digester	1.95 per 5 L cassava slurry; 564 per 50 L digester	68%	[50]
Tapioca wastewater; cow dung	Anaerobic fixed bed polyethylene bioreactor	1.23 per litre of wastewater	ND	[53]
Cassava peels and livestock (cow, pig, poultry) waste	Batch digester; mesophilic; substrate ratio = 1:1	35	ND	[54]
Cassava peels, cow dung and cow pea	Batch digester; mesophilic	Cow pea (87.5); Cow dung (124.3); cassava peels (87.1)	Cow pea (76%); cow dung (68%); cassava peels (51%)	[55]
Cassava stillage (liquid waste) and excess sludge	Batch; two-phase digesters; Thermophilic	Biogas yield not determined; Hydrogen yield of 74 mL/g of volatile solids	62%	[51]
Cassava residues and distillery wastewater	Batch bioreactor; thermophilic	ND	259.46 mL/g-VS[a]	[17]

[a] Methane yield determined after chemical removal of other biogas constituents; ND, not determined.

3.2. Biodiesel

Biodiesel is normally produced from oil-bearing plant crops such as Jatropha, soybean and as well from algal biomass. The lipid content of cassava tubers (Table 1) is unfortunately by far too low for biodiesel production. Hence, it is not an ideal crop for biodiesel production and will therefore not be discussed further in this review.

3.3. Biogas

Most studies done on biogas production from cassava originate from China, Thailand and Colombia and a few African countries such as Nigeria, Tanzania and Kenya. So far studies on cassava biogas production used either raw material from cassava roots, tapioca, tapioca effluent, peels etc. or such materials in co-digestion with cow dung, chicken manure, and food-processing waste and distillery wastewaters to improve the carbon/nitrogen (C/N) ratio. The aim of these experiments is to optimize biogas yields by increasing the methane production. This has been achieved by using different C/N ratios, different digesters, varying microbial inoculant, additional catalysts or additional nutrients. The results of some of these studies are shown in Table 5.

Table 5 shows that cassava roots yielded up to 546L biogas per kg^{-1} total solids (TS) fed into a 50L batch digester [56,57]. A study by Wang [58] compared the yields in single-phase and two-phase anaerobic digesters using cassava stillage and excess sludge. Compared to single phase digestion, the two phase anaerobic digester produced more biogas and the energy yield was 25% higher than that obtained via single phase digestion.

In comparison to other substrates, cassava is well placed in most biogas studies reported in the literature (Table 5). Biogas yields from cassava peels were the highest at 0.61 m^3/kg VS as compared to other agricultural residues such as rice straw, wheat straw and coffee pulp with the exception of maize straw 1 m^3/kg VS [59–61]. However, in reality this comparison is flawed as it is not easily possible to compare the biogas yield results based on substrates and experiments done in different parts of the world. Operating conditions such as temperature, pH, the type of digester used as well substrate compositions are so specific and at the same time so diverse that it is common to get a wide range of values from the same digester even with the same raw material. Because researchers employ different analytical procedures/standards (e.g. L versus nL) across the globe for experiments, results reported may not be comparable.

Co-digestion of cassava with other substrates tends to enhance biogas production (Table 5). Combinations of different substrates often have a synergistic effect on biogas yield due to marked improvement in the balance of nutrients, pH and alkalinity [62]. This was only recently demonstrated by Scherer and Neumann [63] who used compost to increase the biogas yield in sugar beet silage fermentations. Traditionally, cattle manure is used for biogas production followed by manure from pig and poultry. This is believed to safeguard the supply of trace nutrients required [28,63]. More recently, kitchen wastes and crop residues are being exploited for domestic and commercial production of biogas [61,52]. Kitchen wastes contain a high amount of fat in the form of animal fat and cooking oil which enhances biogas yields [53]. For that reason lipid algal biomass and similar substrates from the oceans have also gained considerable attention (Table 6).

3.4. Biogas potential in South Africa

According to the South African Biogas Industry Association (SABIA) [90], biogas potential in South Africa has a market potential of R10 billion (about 1.1 billion USD) and can create 2.5 Gigawatts (GW) of electricity and thousands of jobs for at least 300,000 rural households. The different categories of biomass are estimated to contribute to realization of the renewable energy target by 2050 (Table 7). For example cropped biomass such as

Table 6
Biogas production studies from other substrates with their corresponding characteristics.
Source: Adapted from Rajendran et al. [88]; DM, Dry matter; TDN, Total digestible nutrients; NA, not available; VS, volatile solids; TS, total solids.

Category	Substrate	DM %	Ash %	TDN %	Biogas yield ($m^3\ kg^{-1}$ VS)	References
Agricultural residues	Rice straw	91	13	40	0.55–0.62	[52]
	Wheat straw	91	8	43	0.188	[53,59]
	Maize straw	86	NA	NA	0.4–1.0	[54]
	Grass	88	6	58	0.28–0.55	[14,55,64]
	Fodder beet	16[a]	0.8–0.9	NA	0.278[a]	[65]
	Sugar beet	9[a]	0.5–0.6	NA	0.44[a]	[65]
	Coffee pulp	28	8	NA	0.30–0.45	[14]
	Corn stalk	80	7	54	0.35–0.48	[66]
	Cassava peels (residues)	NA	NA	NA	0.661(0.132)	[17,67–69]
Manure	Pig	20–25	NA	NA	0.27–0.45	[68,70,71]
	Buffalo	14	NA	NA	NA	[72,73]
	Poultry	89	33	38	0.3–0.8	[14,53,64]
	Horse	28	NA	NA	0.4–0.6	[74,75]
	Cow	38	14	92	0.6–0.8	[72,76–82]
Faecal matter	Human excreta	20	NA	NA	NA	[76,83]
Food waste	Whey	94	10	82	NA	[62]
	Fruit waste (apple)	17	2	70	NA	[53,83]
	Vegetable waste	20	NA	NA	0.4	[76,81,83]
	Kitchen/restaurant wastes	27/13	013/8	NA	0.506–0.65 (CH_4)	[62,82,84,85]
	Left over's food	14–18	NA	NA	0.2–0.5	[54]
	Egg waste	25	NA	NA	0.97–0.98	[54]
	Cereals	85–90	NA	NA	0.4–0.9	[54]
Aquatic plants or Seaweed	Algae	NA	NA	NA	0.38–0.55	[86]
	Salvinia	NA	NA	NA	0.155	[87]
	Water hyacinth	7	NA	NA	0.2–0.3	[52,87]
	Giant kelp	NA	NA	NA	NA	[14,64]
	Caboma	NA	NA	NA	0.221	[87]

[a] Data from CROPGEN [89] database.

Table 7
Biogas potential in South Africa by 2050.

Biomass	Estimated Energy	Reference
Cropped biomass (10% of suitable land) e.g. cassava, parks and gardens materials	1,350 Petajoules (PJ)	[91]
Solid waste in metropolitan areas (landfills)	5,000 Gigawatt hours (GW h)	[92]
Wastewater in municipal water treatment plants	9,000 GW h	[93]
Farms/homesteads	5–10 kW thermal energy	[93]
Cow manure		
Eco-sanitation		
Urban gardens		
Bio-centre sanitation		
Breweries	50 Kilowatts–5 Megawatts thermal energy (MW_{th}) on industrial scale	[93]
Fruit processing		
Stock farming		
Abattoir wastes		
Silage maize	5–10 MW_{th}	[93]
Algae grown on sewage maturation ponds		
Comparing figures		
Eskom (2011) electricity output	224,000 GW h	
White Paper (2003) Renewable energy target for (2013)	10,000 GW h	[94]

cassava and other energy crops are estimated to produce biogas equivalent to 1350 Petajoules (PJ) of electricity [91] while biogas energy from solid waste in metropolitan areas (landfills) is estimated at 9000 gigawatts electricity equivalent [92]. A summary of the biogas potential for various categories of biomass is shown in Table 7.

4. Biogas production from cassava

Biogas is a product of a microbial process known as anaerobic digestion (AD). Anaerobic digestion involves microorganisms decomposing organic matter in the absence of oxygen to produce mainly methane and carbon dioxide. The residues left after AD adds value to the process as they can be used for agricultural purposes as fertilizer. Other important applications of AD include the reduction of sludge volume generated from wastewater treatment processes, sanitation of industrial organic waste, and benefits from degassing of manure. Renewable energy production, integrated bio-refining concepts, and advanced waste handling are delineated as the major market players for AD that likely will expand rapidly in the near future [95].

Anaerobic digestion involves a combination of basically four processes namely, hydrolysis, acidogenesis, acetogenesis and methanogenesis. The first stage, hydrolysis is where complex insoluble polymeric organic matter such as carbohydrates, fats and proteins are enzymatically hydrolysed into simpler soluble organic materials

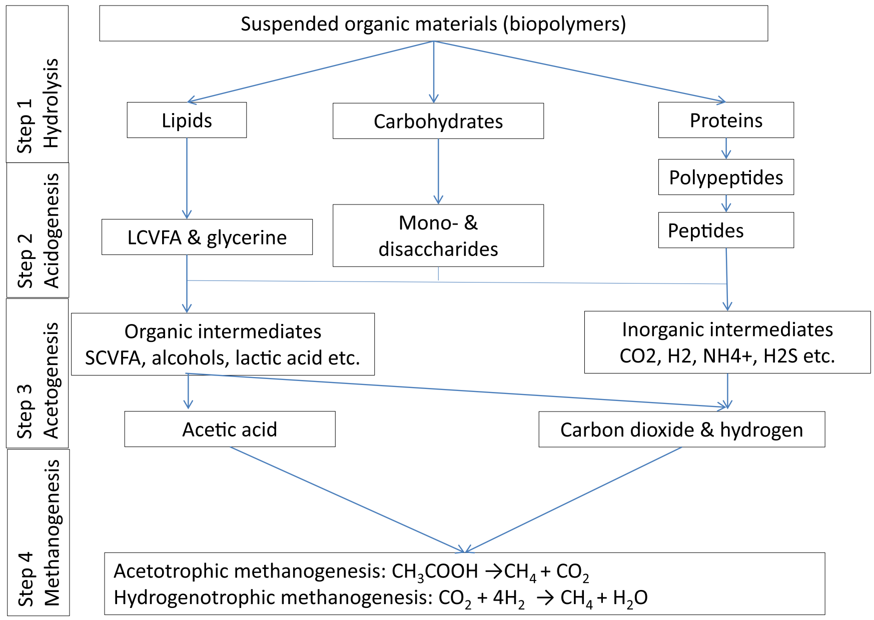

Fig. 3. Stages of anaerobic digestion for biogas production [95].

Table 8
Advantages and disadvantages of adopting different bioreactor configurations extracted from the available literature.

Process condition	Advantages	Disadvantages
Batch	Treats high solids content (above 25%) Can digest fibrous and difficult wastes Suitable for discontinuous biomass supply Simple and very small water usage Low tech and cheap for developing countries	Requires new seed every time Large retention times (1–2 months) Clogging Stratification of different layers Variable biogas production (normal distribution (bell-shaped pattern)
Continuous	Smaller retention time Treats larger quantities of biomass over a period of time Constant biogas production Higher efficiency	Treats smaller solids content at a time More expensive to set up Requires bulky agents
Single stage	One tank usage reduces construction cost Known process	Less control of reactions within the system Short-circuiting Stratification of different layers Decreased biogas production Less kill-off of microbial pathogens
Multi stage	Larger overall reaction rate Larger biogas yield Increased biological stability High cell densities of methanogens Design flexibility	Complex Smaller biogas yield when solids are not methanogenized More expensive to set up
Dry fermentation	Treats high solid content (25–40% TS) Very small water usage Smaller heat pre-treatment No moving parts	Slower onset of gas production More energy to operate Less material circulation Less contact between bacteria and substrate
Wet fermentation	Low energy input More contact between microorganisms and substrate Faster onset of gas production	Low solid content (5–15% TS)
Mesophilic (25–45 °C)	Less heating More stable and tolerant to environmental changes but not in all cases	Longer retention times (15–30 days)
Thermophilic (45–57 °C)	Higher growth rate of bacteria and Euryarchaeota Faster gas yields Shorter retention times (12–14 days) Higher gas production Elimination of susceptible potential pathogens in digestate	Less stable to environmental changes except in energy crop fermentations where they promote hydrogenotrophs over acetotrophs Energy input costs overrides biogas cost savings Requires more effective control

like sugars, fatty acids and amino acids. In the second stage, acidogenesis, a further breakdown of the material occurs through fermentation by acidogenic bacteria to produce ammonia, carbon dioxide and hydrogen. Other low molecular weight organic compounds such as carbonic acids and alcohols are also produced [96]. Further digestion of these molecules in the acetogenesis stage produces mainly acetic acid, hydrogen and carbon dioxide. Methanogenesis is the final stage where the products of acetogenesis are converted by methanogenic *Archaea* into a mixture of methane and carbon dioxide, known as 'biogas' (Fig. 3) [96].

4.1. *Techniques for cassava biogas production*

Biogas production from cassava requires selection of an appropriate system from various digester techniques together with proper digester design. This requires a thorough grasp of the technologies used in various parts of the world that have proved successful. The various techniques and advantages and disadvantages of each of them are explored as follows. The most promising technologies applicable for cassava biogas production are highlighted where necessary and combinations of technologies where appropriate are recommended. However, the final choice of design and technology lies with the investigator or stakeholder. A summary of the potential pros and cons of each of the digester configurations is shown in Table 8.

Fermentations for biogas production are performed in anaerobic digesters. There are different digester-configurations depending on the process condition selected which may be either:

- Batch or continuous.
- Two-phase or two-stage.
- Dry or wet mode.
- Mesophilic or thermophilic.

4.1.1. *Batch or continuous digestion of cassava biomass?*

A batch system is the simplest form of digestion. Cassava biomass is added to the digester at one time and the digester is sealed for the duration of the process. After digestion, the effluent is removed with having contact with new substrate load [96]. Such a simple batch system has been used to produce biogas from cassava biomass [56].

In a continuous process, the cassava biomass is added constantly or in stages while the end-products are constantly or periodically removed. Ideally, the amount of raw materials in is equal to the amount of slurry leaving the digester and hence special consideration should be given to the proper design of the inlet and outlet of the raw cassava and slurry, respectively. This results in a constant amount of the production of gas. An example is the plug-flow CSTR (continuous stirred tank reactor) used for cassava biogas production [54].

4.1.2. *Two-phase or two-stage process? An overview*

The main idea behind two-phase digestion is to separate the anaerobic food chain into two microbiological processes (Table 9); hydrolytic/acidogenic phase (first stage) and acetogenic/methanogenic phase (second stage).

The objective is to provide an optimal environment for each of the distinct microbial populations performing these biochemical transformations, thus allowing an overall faster reaction [97]. The combined tank size of the first and second phase is reduced when compared to the conventional systems. Various studies [54,97,98] claim the two-phase digestion system would result in a greater yield of methane due to a larger fraction of the substrates being converted to biogas by the more vigorous activity of the acidogenic microbes.

However, the different microorganisms involved work commensally and depend on each other for optimal metabolism. The hydrogen and acetate as well as other alcohols and higher fatty acids formed by acidogenic microorganisms tend to inhibit their own metabolism especially at lower pH values enabling the acids to enter the cells. In fact, methanogens are important as they can remove acetic acid (acetotrophic methanogens) and hydrogen (hydrogenotrophic methanogens) by converting them to methane. At the same time the presence of the different members of the anaerobic food chain in the same microenvironment enables syntrophic metabolism as for example ethanol is only fermented to acetate if the hydrogen formed is simultaneously consumed by hydrogenotrophic methanogens via interspecies hydrogen transfer [99].

Although some acidogenic microbes such as *Clostridium* spp. and *Peptococcus* spp., are well known to tolerate the low pH that develops in the first phase, a low pH does not actually help the process of acidogenesis [97]. In fact, the main advantage of overall size reduction claimed by most researchers over several decades for systems using dairy waste has not been demonstrated. In these specific cases, the operation of two rather than one digester is not a clear advantage [97]. However, for a crop fed digester, the operation of two stage fermentation can be better [100,101].

In summary, in the so-called two-phase digestion processes methane is produced in both stages. The first tank merely acts a sludge tank, sometimes with a recycle loop from the second to the first stage, which somewhat contradicts the aim of a two-phase process. Perhaps an obvious advantage of the two-phase digestion system is the reduction of short- circuiting, a real problem with single-phase mixed reactors [97]. Short-circuiting refers to the passage of a fraction of the cassava feedstock through the bioreactor with a shorter retention time than the average retention time of the bulk stream. This normally leads to a decreased biogas production and lesser kill-of microbial pathogens [102].

4.1.3. *Dry or wet mode cassava fermentation*

Dry mode cassava fermentation involves mixing cassava biomass with an inoculum usually obtained from fermented cow manure [103]. Two main systems are normally used for dry fermentation viz. the percolation and the bed system. In the percolation system, the input is stacked up in a gas-tight container and left to ferment for a period of time while simultaneously spraying with optionally preheated circulating water [104]. The bed system works essentially without water [104]. Dry fermentation of cassava tubers is possible

Table 9
Characteristics of the first and second phase anaerobic digestion processes.

Hydrolytic/Acidogenic phase (First stage)	Acetogenic/Methanogenic phase (second stage)
Hydrolytic/acidogenic microbes in action	Acetogenic/methanogenic microbes in action
Very short hydraulic retention times (HRTs)	Longer HRTs >15 days
Short solid retention times (SRTs)	Longer SRTs
Organic acid formation	Conversion of acids to methane
Acidic (low) pH	Neutral Ph
Smaller tank size	Larger tank size

since it contains about 65% moisture, but like other plant-based substrates, will need to be crushed to increase the surface area before stacking up the digester. However, this technology is not yet developed to its full potential for cassava [105].

Wet mode cassava fermentation typically involves mixing the biomass with water before stacking up the fermentation tank. The whole process requires regular or even better continuous mixing in order to prevent sinking or flotation of the solid materials. Ammonia accumulation is a critical parameter in wet fermentation as it inhibits the microbial process at pH values above 7 when ammonia, the form which can permeate biological membranes, is the main form present. Wet fermentation may therefore not be suitable for grass silage with very high nitrogen content ($\pm$1%) compared to cassava with very low nitrogen content. During fermentation, nitrogen is normally converted to ammonia or ammonium depending on the temperature and the pH with potentially adverse consequences to the microbial process [106]. Usually, wet fermentation is suitable for cassava biomass and most energy crops.

In a study by Vogel et al. [104], dry and wet fermentation were combined to test the effect on biogas yield from herbaceous biomass. The results showed that the combination does not lead to a higher biogas yield. However, the percolation system yielded more biogas than the bed system. The suitability of percolation system for cassava biogas production through dry fermentation presents a direction of research for the future.

4.1.4. Mesophilic or thermophilic digestion of cassava biomass

A digester can be classified as either mesophilic or thermophilic depending on the temperature employed and the species of methanogens involved in its digestion [107]. Most mesophilic operations reported in the literature were run within a temperature range from 20–45 °C with an optimal temperature of 30–38 °C. Less than 10 °C as operational temperature – thus psychrophilic – was recorded in Bolivia [108] but the process was three times slower than normal which is not surprising based on microbiological grounds. While mesophilic prokaryotes are believed to be more tolerant to changes in the environment than their thermophilic counterparts [96], recent studies indicated that this assumption might not be correct [109]. Thus the mesophilic systems might be more stable if the prevailing conditions favour the mesophilic prokaryotes. In a thermophilic digester, the operating temperature typically ranges from about 50–60 °C which in turn requires more energy input to maintain the elevated temperature. However, the higher temperature increases the rate of reaction and faster breakdown of organic matter by the thermophiles, thus increasing the rate of biogas production. At the same time it is able to inactivate a potential pathogenic bacterium which is not the case under mesophilic conditions [109]. Thus a disadvantage of thermophilic digestion is the high energy input which often overrides the benefits of increased biogas production [96].

4.2. Microbiology and biochemistry of cassava biogas production

The biogas production from cassava biomass through AD processes involves complex interaction between different microorganisms with every biochemical step occurring under specific conditions. This means that for a productive anaerobic process, a proper balance must be ensured. A balanced methane production process involves both facultative and obligate anaerobic microorganisms that are part of the microbial community. It involves an array of different microbial groups, viz., hydrolytics, fermenting acidogenics, fermenting acetogenics, and methanogenic prokaryotes all acting at different stages for the final production of biogas (Fig. 4).

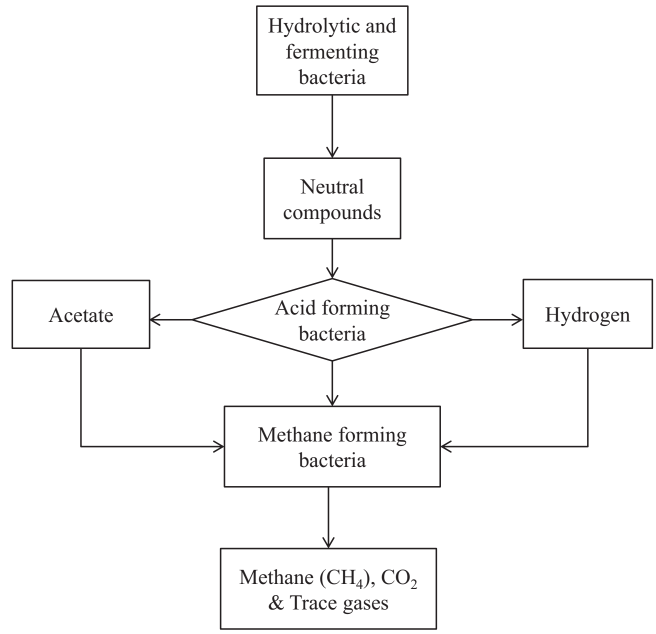

Fig. 4. Pathway showing principal microbial processes involved in anaerobic digestion of cassava for biogas production [166].

Important microorganisms involved during the hydrolysis stage are for example *Clostridium* spp., *Ruminococcus* spp., and *Bacteroides* spp. In this stage, complex organic matter (in the form of particulates and polymers) are depolymerized, broken down or liquefied to simple monomers such as sugars and amino acids. Factors like substrate availability, microbial population density, pH and temperature often determine the rate of hydrolysis. The substances with the highest rate of hydrolytic degradation are polymeric carbohydrates such as starch followed by lipids, proteins and hemicellulose. Hence for cassava processing wastewater, it was shown [110] that species such as *Clostridium acetobutylicum* can efficiently produce hydrogen thereof which in turn can feed hydrogenotrophic methanogens. While cellulose is slowly hydrolyzed, lignin is not hydrolyzed by most microbes. Current research efforts are therefore mainly geared towards finding microorganisms with lignolytic ability as this would enable a better utilization of the lignin fraction of plant biomass [111]. Substrates such as municipal solid wastes (MSW) only have about 50% of its organic matter hydrolyzed while other substrates have less or higher percentage depending on pre-set conditions [112]. The rate of cassava biomass hydrolysis can be improved by increasing the pre-treatment temperature, thus making it more soluble [16]. This leads to increased rate of biogas production resulting in an increase in biogas yield.

The acidogenesis stage usually involves the action of fermentative microbes. Fermentation is used to describe the energy yielding process where organic molecules serve as both electron donors and electron acceptors. During fermentation, the molecule metabolized does not have all its potential energy extracted. In other words, the molecule is not completely oxidized. In the acidogenesis stage, the soluble compounds are transformed in the presence of facultative anaerobes by fermentation to various volatile fatty acids (VFA) or alcohols such as propionate, butyrate, succinate, or ethanol. The reactions produce acetic acid from amino acid like compounds while hydrogen and carbon dioxide typically result from the catabolism of carbohydrates and other simple alcohols. Typical microbes involved in these reactions for a variety of substrates including cassava are *Peptoccus* spp., *Clostridium* spp., *Lactobacillus* spp. and *Propionibacterium* spp. However, for the digestion of crops in the presence of manure, members of the class *Chloroflexi* and the genus *Clostridium* usually associated

with hydrogen production, were found as dominant bacterial groups [113].

The formation of acidic species in the anaerobic digestion process has a tendency to lower the pH of the reaction medium. Ammonia released from the degradation of amino acids and proteins form ammonium bicarbonate (NH_4HCO_3) at neutral pH which acts as a potential pH buffer. A sharp drop in pH is a clear indicator of the overproduction of volatile fatty acids (VFA's), which can lead to a bioreactor failure. The proportion of oxidized compounds is dependent on the quantity of dissolved hydrogen. It is therefore essential to avoid the accumulation of hydrogen by promoting the activity of hydrogen consuming methanogens as this will otherwise negatively affect cassava biogas production by lowering the pH [114].

Acetogenesis is an oxidation step in the anaerobic digestion process. At this stage microbes degrade the longer chain fatty acids via an oxidative reaction facilitated by obligate acetogenic bacteria. The external electron acceptor (protons or carbon dioxide) is maintained at low concentrations with higher organic acids degraded to acetate via β-oxidation. The main microbes involved in these reactions are *Syntrophobacter* spp., *Desulfovibrio* spp. and *Syntrophomonas* spp. Syntrophic metabolism as for the example of ethanol fermentation shown below will lead to the production of acetic acid, methane and hydrogen [99]:

$$\underset{\text{Ethanol}}{2CH_3CH_2OH} + \underset{\text{Water}}{2H_2O} \rightarrow \underset{\text{Aceticacid}}{2CH_3CO_2H} + \underset{\text{Hydrogen}}{4H_2} \quad (\Delta G^\circ \sim +19\ \text{kJ/mol}) \tag{1}$$

$$\underset{\text{Hydrogen}}{4H_2} + \underset{\text{Carbon dioxide}}{CO_2} \rightarrow \underset{\text{Water}}{2H_2O} + \underset{\text{Methane}}{CH_4} \quad (\Delta G^\circ \sim -131\text{kJ/mol}) \tag{2}$$

$$\underset{\text{Ethanol}}{2CH_3CH_2OH} + \underset{\text{Carbon dioxide}}{CO_2} \rightarrow \underset{\text{Acetic acid}}{2CH_3CO_2H} + \underset{\text{Methane}}{CH_4} \quad (\Delta G^\circ \sim -112\text{kJ/mol}) \tag{1+2}$$

The methanogenesis phase of anaerobic digestion involves methanogenic *Euryarchaeota* which are the microorganisms responsible for the acetotrophic and hydrogenotrophic generation of methane as summarized below.

$$\underset{\text{Acetic acid}}{CH_3CO_2H} \rightarrow \underset{\text{Methane}}{CH_4} + \underset{\text{Carbon dioxide}}{CO_2} \tag{3}$$

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Hydrogen}}{4H_2} \rightarrow \underset{\text{Methane}}{CH_4} + \underset{\text{Water}}{2H_2O} \tag{4}$$

In addition to these two well-known ways of producing methane, it can be produced similarly from substrates such as formic acid, methanol, methylamine or carbon monoxide [115–118]. It was long assumed that about 70% of total methane formed during biogas production stems from acetoclastic methanogenesis and the main prokaryotes responsible for this reaction are *Methanosarcina* spp. and *Methanosaeta* spp. while the remaining 30% of the total methane is formed via hydrogenotrophic methanogenesis with *Methanobacterium* spp. and *Methanobrevibacter* spp. being the main organisms responsible [119]. However, this assumption is based on studies dealing with wastewaters while more recent studies using energy crops as fermentation substrate indicate that this assumption may not be correct for these substrates. Recent studies showed [21,109,113] that hydrogenotrophic methanogens dominated within the population of methanogens in fodder beet silage fed anaerobic digestion processes. Similar results were obtained in mesophilic anaerobic digesters fed with maize and rye [120–122].

5. Optimization of cassava biogas production

Most of the techniques used to improve biogas production and methane yields at landfills and wastewater treatment plants also apply to cassava biomass because of its organic material content. The rate of biogas production depends on three main factors; the degree of hydrolysis, the rate of production or consumption of intermediates, and the rate of methanogenesis. Therefore, optimization of cassava biogas production is based on the need to improve material digestibility and biological activity in the anaerobic digester.

Popular techniques include pre-treatment of the feedstock, the use of two-phase digestion (see Section 4.1.2), and co-digestion with two or more additional feed stocks [15,68,123–126]. The purpose of pre-treatment is to increase the substrate availability and the degree of hydrolysis of the feedstock while the use of two-phase digestion and microbial stimulants is intended to enhance the ultimate methane yielding step. Pre-treatment is discussed below in more detail as a potential method to improve cassava biogas production.

5.1. *Potential pre-treatment techniques for cassava biomass—An overview*

Based on what is known for the anaerobic digestion of other energy crops and cassava based studies, possible pre-treatment techniques include mechanical, ultrasonic, thermal, chemical and biological procedures. Combinations of the above pre-treatment options are also possible [127]. Thus it appears that a combination of mechanical, biological and chemical pretreatment technology is a suitable approach for cassava biomass. The differences in conversion technologies lie mainly in the temperatures used to deconstruct the biomass structure, the intermediate products generated via the breakdown procedure and the enzymes that convert those intermediates to biofuels. In traditional biochemical conversion processes, the biomass is chemically pretreated and fed to hydrolytic enzymes that liberate the sugars from biomass. The resulting sugar-rich stream (hydrolysate) is fed to microorganisms that ferment the sugars to biofuels such as methane under anaerobic conditions. The biochemical route also uses a combination of biocatalysts and mechanical pretreatments to produce sugars and other intermediates which are upgraded to biofuels by fermentation. The traditional route is still very relevant to Africa and other developing economies because of the higher cost involved in going through the biochemical route. A summary of pre-treatment methods coupled with their potential advantages and disadvantages is shown in Table 10.

5.1.1. *Mechanical pretreatment*

Mechanical pretreatment involves the physical dispersion of substrate components thereby decreasing their particle size thereby increasing the surface area available. Cassava size reduction facilitates faster moisture adsorption and makes nutrients

Table 10
Advantages and disadvantages of different biomass pretreatment techniques.

Type of pretreatment	Treatment method	Reported advantages	Reported disadvantages	References
Mechanical	Stirred ball mills (SBM)	10–30% solubilisation 10–20% increase in biogas	Capital and operational costs Poor dewaterability	[98,142,143]
	High pressure homogenisation (HPH)	Up to 50% solubilisation 30% increase in biogas	High capital and operational costs	
	Mechanical jet smash (MJS)	Similar to HPH	Poorly studied	
	High performance pulse (HPP)	High degree of solubilisation	Expensive Subject to wear	
	Lysate centrifuges	5–10% solubilisation 10–30% increase in biogas	Centrifuge installation costs	
Ultrasonic	Low or high frequency ultrasound	Increased sludge disintegration Cell lysis increases soluble COD content 50–70% increase in biogas Enzyme integrity intact Low operational cost Improves dewaterability	Initial energy input Unsuitable for lignocelluloses High capital cost Negative dewaterability (Lab scale)	[88,89,98]
Thermal	Heat (Laboratory)	25–50% solubilisation Potential combination with chemical (wet explosion) 25–100% increase in biogas Improves dewaterability	Increase in non-degradable COD	[59,96,144]
	Heat (commercial)	30% solubilisation 50% increase in biogas	High capital and operational cost Serious odour problems	[56]
Chemical	Alkaline	30–60% solubilisation 25–100% increase in biogas Low Capital costs	Increase in non-biodegradable COD Operational costs may go high	[100,142]
	Ozone	30% solubilisation > 100% increase in biogas	Destruction of structure Denaturation Serious odour problems Poor dewaterability Uneconomical on a large scale	[101]
Biological	Microbes, enzymes	10% solubilisation Low Capital costs Potential combination with mechanical pretreatment	Unclear treatment costs Odour problems	[142] [142]
	Probiotics	50% solubilisation 10–100% increase in biogas	High operational costs Uneconomical and odour	[17,69]

easily available for the microorganisms that are responsible for anaerobic fermentation and hence leads to better methane gas production. Lysis of the cassava cells which usually occurs can be monitored by the increasing soluble chemical oxygen demand (COD) content of the substrate. This method requires initial energy input to disrupt non-covalent forces between the cassava cells. Chemical modifications of the organic matrix rarely occur and may not be significant when it does. Approximately 60% increase in soluble COD content has been observed using mechanical pretreatment of municipal solid waste (MSW) [128]. Impact grinding has been used to increase the soluble COD content of organic fractions of municipal solid waste (MSW) by approx. 2.5 times [113]. Research focusing on the efficiency of such pre-treatment on cassava and the effect of cassava particle size on the methane production in anaerobic fermentation processes is therefore required.

In addition, this mechanical method has been claimed to maintain the integrity of the plant enzymes [129] and to improve the digestion of energy crops. For cassava biomass, the major issue with using this method is the energy required for grinding which may offset any gains made in biogas production.

5.1.2. Ultrasonic pretreatment

Laboratory scale studies using ultrasonic pretreatment have shown variable degrees of solubilisation (30–90%) and increases in biogas production (5–70%). However, it requires high energy input and capital costs. A study by Lehne et al. [130] reported a concomitant reduction in the average particle size with an increase in the degree of disintegration of the sewage sludge but this may not be suitable for energy crops such as cassava. Vera et al. [131] used ultrasound of low and high frequency to disintegrate sewage sludge effectively which consequently increased the fermentation rates but again this may not be suitable for plant biomass. Using ultrasound may not be ideal for cassava biomass due to expected high energy input required to disintegrate the cells.

5.1.3. Thermal pretreatment

Temperatures just below 100 °C are used to break up plant cells by increasing membrane fluidity and hydrolyzing polymers resulting in a soluble COD release of about 35%. This method causes modifications in the chemical equilibrium of the exopolymers in lignocellulosic biomass [61,132].

Thermal pretreatment can increase the biogas production and methane yield of certain substrates but is not an effective pretreatment technique in all cases. For example, the thermal pretreatment of water hyacinth at 80 °C increased the solubility only slightly with little or no effect on anaerobic digestion [133]. While pasteurization of a abattoir waste at 70 °C for 1 h produced a fourfold increase in methane yields [134] this might not be applicable to more stable plant based biomass. Thermal pre-treatment may be used for cassava but its cost must be weighed against the benefits derived from increased biogas production rates.

5.1.4. Wet explosion pretreatment

Wang et al. [126] used wet explosion as a pre-treatment to enhance methane production from energy crops such as cassava and other agricultural residues. The results showed that an

increased sugar release after pre-treatment does not automatically imply higher methane yield. The wet explosion process was developed by Ahring and co-workers [135] in 2006 as a combination of thermal and chemical oxidation to treat high biomass concentrations. However, biogas production was not significantly increased by this technique and may not be necessary to use with cassava.

5.1.5. Chemical pretreatment

Solubilisation (30–60%) of insoluble substrates has been achieved using either alkaline [136] or ozone pre-treatments [137]. Ozone treatment produced >100% increase in biogas production while alkaline treatment produced 25–100% increase in biogas yields as well as methane. The main disadvantage of chemical treatment lies with the cost of acquiring the chemicals. On a commercial scale, ozone treatment is highly uneconomical [138]. However, this method has been used successfully by Zhang et al. [139] for the treatment of cassava with reported methane yields of 259.46 mL/g of VS destroyed.

5.1.6. Biological pretreatment

Enzymes and probiotics are used as biological treatments to achieve 10–50% increased solubilisation of substrates [17,100]. Both treatments require low capital costs; however operational costs are usually high rendering them uneconomical. An additional disadvantage is the level of odour generation typically experienced with biological treatments. Notwithstanding the odour problem, >100% increase in biogas production have been achieved for cassava using such pre-treatments [17]. The use of biological pretreatment is highly recommended for cassava provided the operational costs are significantly reduced by sourcing cheaper supplies.

5.2. Use of microbial stimulants

Microbes can apparently be activated using saponified steroids. Examples are commercially available formulations named Aquasan® and Teresan® (Amit Chemicals, India). Both products are plant-derived and apparently work by interfering with microbial enzyme activity. They are supposed to stimulate microbial metabolism thereby increasing the rate of substrate digestion. These products also restrict odor emissions by interfering with enzymes involved in odor production. A dosage of 15 ppm Aquasan® was reported to generate biogas production with 55% higher yields than when using untreated cattle manure [97]. Singh et al. [140] produced 34.8% more biogas from a mixture of cattle manure and kitchen waste using 10 ppm Teresan.

Another product called BioCat+® was tested in a case study in Switzerland [141]. Biocat+® is a cocktail of microorganisms and cofactors which has been claimed by the company to stabilize most digester systems. The results with BioCat+® showed a significant reduction in the bad odours released by the digestate. It apparently consumed the volatile acids largely responsible for smells and the biogas production potential was increased by 30% [141]. However, it is not clear without research whether these microbial stimulants will be applicable and efficient for the anaerobic digestion of cassava biomass.

5.3. Co-digestion of cassava biomass with other substrates

Co-digestion improves the nutrient balance of total organic carbon, nitrogen, and phosphorous content of a feedstock, resulting in a stable and maintainable digestion process and resulting in good fertilizer quality [145]. Co-digestion also improves the flow qualities of the co-digested substrates. Increased biogas production from the co-digestion of livestock waste and cassava peels has been documented [14]. Wang et al. [68] investigated the thermophilic co-digestion of cassava stillage and cassava excess sludge for methane and hydrogen production and found that the hydrolysis process was significantly improved by the excess sludge recycling in the biogas production phase.

5.4. Optimizing the productivity of methanogens—An overview

Optimizing the productivity of methanogens is a way forward for scientists to understand and improve biogas production from biomass [111]. This approach requires a thorough understanding of the microbial metabolism and growth and activity of the responsible microorganisms in relation to anaerobic digestion for biogas production. This review will only briefly highlight the basics as more detailed information on microbial growth and metabolism within the anaerobic food chain is available [109,117].

About 90% of the microbial biomass is organic matter, about 70–80% water, 10–20% dry matter and 10% inorganic materials [146,113]. Major cellular materials include proteins (55% of dry weight), 20.5% ribonucleic acid (RNA), 9.1% lipid, 5% polysaccharide and about 3.1% deoxyribonucleic acid (DNA). Other materials include sugars, amino acids and inorganic ions which constitute about 6.3% dry weight of the typical microbial cell. The main elements in a microbial cell are carbon (50% dry weight), oxygen (22%), nitrogen (12%), and hydrogen (9%). Other elements present in small amounts are phosphorus, sulphur, potassium, sodium, calcium, magnesium, chlorine, iron and trace elements. The dry weight of the organic fraction found in microbial cells is approximately 53% of carbon.

Microbial metabolism involves different strategies for meeting its ultimate need to synthesize adenosine triphosphate (ATP), the central energy currency of the cell. The microbial cell requires this energy to perform chemical work such as the synthesis of complex organic molecules from simpler precursors essential for its growth, reproduction and maintenance as well as for motility and active transport of nutrients.

Although methanogens – like the other members of the anaerobic food chain – may receive all the nutrients they need, they will not grow and multiply unless other environmental conditions such as oxygen concentration, acidity, alkalinity, and temperature are favourable [111]. The response of methanogenic *Euryarchaeotes* as well as that of the bacterial members of the anaerobic food chain to these factors and process parameters such as hydraulic retention time or organic loading rate will present an interesting research endeavour for the future and is vital to better understand the microbial influence on biogas production.

6. Discussion

Some people have criticized the biogas-from-energy crops development in Africa based on the food versus fuel debates highlighting the following: (a) potential increase in food prices due to competition with biofuel industries; (b) possible dispossession/acquisition of land from rural dwellers and (c) possible diversion of resources from food to fuel thus threatening food security. However, the current biogas-from-energy crops developments in Africa are planned in such a manner that they take into consideration all these concerns. According to the 2013 report of the American Academy of Microbiology, Africa and the rest of the developing countries face a serious problem which is the availability of sustainable and renewable energy. There is a need to feed the growing population whilst at the same time the growing population increases the need for affordable and more sustainable energy to lessen damage to the environment. The current trend is therefore to pay more attention to develop appropriate and

sustainable renewable energy technologies that can be used in the African context, ideally enabling emerging and small scale farmers to participate in this development.

Scientists are divided across both sides of the food versus fuel debate. Protagonists of food security argue that using energy crops for energy is more resource-intensive requiring the diversion of agricultural land that could otherwise be devoted to food production. The additional concern raised is that forests could be destroyed to provide more agricultural land as is the case in Brazil to enable large scale bioethanol production [147]. Also mentioned are detrimental impacts such as strain on water resources, increase in soil erosion, coupled with negative energy balances and poor greenhouse gas (GHG) benefits [148,149]. On the other side of the debate, scientists have argued the need to curb fossil fuel use to slow the emission of greenhouse gases that are contributing to global warming. Furthermore, at the local level, rural communities struggle to attract enough business to anchor their economies and provide enough jobs even for lesser skilled citizens [150]. The curbing of fossil fuel use means that other sources of energy are required to meet the growing demand.

This debate is not new as it started way back in the 1970s. There are many concerns raised by the biofuel critics, some of which are already mentioned above. According to Rosillo-Calle and Johnson [151], the land area required and the category of land to be used is at the heart of the debate. Current and future global estimates for land use of biofuels range from 40–800 million hectares [152]. The agricultural land for Africa in 2009 comprised pasture (30.6%), arable land (7.6%) and land for permanent crop (1%), for a total of 39.2% higher than world levels [153]. There is more pasture land in Africa than crops and arable land. Within the African continent, the largest areas of arable land (0.3%) are located in Central Africa and Southern Africa.

Planting the second generation of biofuel feedstock on abandoned and degraded cropland and low-input high-diversity (LIHD) perennials on grassland with marginal productivity may fulfil 26–55% of the current world fuel consumption, without affecting the use of land with regular productivity for conventional crops and without affecting the current pasture land [154]. Under the various land use scenarios, Africa may have more than one-third, and together with Brazil, may have more than half of the total land available for biofuel production [154].

It is beyond the scope of this paper to go into more detail regarding this ongoing debate. However a few pro-biofuel arguments will suffice:

- Biofuels are a good alternative to fossil fuels for non-oil producing countries that are secure in terms of food supplies and who already spend a large portion of their national income on fuel imports.
- Agriculture in developing countries requires modern energy systems and the availability of bioenergy can actually enhance food production.
- A mutually beneficial agricultural system can produce both food and energy crops in a sustainable manner.
- The use of certain biofuel crops with good water footprint can prevent soil degradation and reclaim marginal and degraded lands.
- The socioeconomic and environmental benefits of biofuels far outweighs its potential negative impacts with good agricultural management practices.
- Bioenergy can play an important role in modernizing and diversifying agriculture, bringing in new investments and consequently enhancing food productivity.
- Agriculture at the moment is plagued by too much wastage and low crop yields which can be greatly enhanced through bioenergy.

On the negative energy balances and poor GHG benefits, the pro-biofuel group argued that on the basis of life cycle analysis conducted in recent literature, biofuels provide a net GHG benefit of 30–100% compared to petroleum fuels if land conversion emission is excluded [155]. And they argued that, in general all biofuels have energy balances greater than fossil fuels [151]. Some energy crops such as cassava and sugarcane have energy balances >9 since their energy depends not only on the feedstock productivity but also on the biomass residues and peels (for cassava) as energy input.

It is of note that the current drought in the US, Australia, India, Russia and Ukraine has fuelled this debate even more and has strengthened to some extent the anti-biofuel lobby group case. However, the rise in food prices may not be blamed solely on biofuels. It is our view that agriculture has an important role to play in stopping this debate. According to Beddington et al., [156] "agriculture is at the nexus of three of the greatest challenges of the 21st century; (i) achieving food security (ii) adapting to climate change and (iii) mitigating climate change whilst in the midst of growing demands for clean water, energy and land resources.

The big question is how can we produce enough food for the growing population and at the same time stabilise our own climate system? Agriculture is both part of the problem and part of the solution [152]. We must move away from inefficient farm practices and embrace technology to boost food production and feedstock. Farming cannot be seen as a backward activity but as a science driven industry with the capacity to produce more food, energy and industrial products [157]. A transformed agriculture could attract new investments on modern scientific research with potential to increase crop yields. According to Hazell and Wood [158], it took England 1000 years to increase the yield of wheat from 0.5 to 2.0 t per hectare per year but just 40 years to increase it to 6 t per hectare per year. For the African continent, studies have shown that with vast amount of idle land available, food security in the sub-Saharan Africa would not be significantly affected by the expansion of biomass to energy. Instead, by modernising agriculture and reducing foreign energy imports, biomass to energy could actually enhance economic development [159,160].

Another pertinent question is how do we tackle the growing agricultural and food waste? This is an area that most protagonists of food insecurity tend to ignore. The wastefulness of the current agricultural practices is huge. For example, Americans waste 40% of the food supply every year estimated to worth $165 billion annually [161]. About 30–50% of food rots away uneaten, 75% of fresh vegetable harvest is lost [162]. Such waste materials should be utilized to generate energy which in turn can support the production of food amongst other applications.

Without alternative energy inputs such as from biofuels, agriculture would not be able to feed the growing population as an increased productivity requires increasing energy input while the alternative is reliance on human power, low productivity and extensive land cultivation [163]. Clearly bioenergy and agriculture have to be seen as mutually beneficial activities. Hence the following points are worthwhile to be considered:

- To use bioenergy in niche areas such as transport, commercial farming ventures (combined heat and power (CHP) and rural households.
- To avoid land grabbing in developing countries at the expense of staple food crops.
- To use most suitable feedstock that are economically and environmentally viable.

- To pay particular attention to crops that have increased drought and pest tolerance and require only minute fertilizer input and are therefore suited for biomass production in areas where food crops cannot be produced while at the same time exhibiting sustainable water footprints.
- To establish a complementary food and biomass to energy production which takes all stakeholders on board.

Cassava is a crop that can thrive in all agro-ecological zones thereby enabling its use in currently non-utilized and degraded areas of land. Cassava biomass therefore has potential to be used as industrial crop for biogas production in South Africa thereby using land not suitable for food production. [39,40].

However, the sustainability of cassava biogas production in Africa depends on technological and economic factors. Technological advances in biomass-to-energy conversion and feedstock productivity will determine the future cost. The relation between capital costs and plant size will normally determine the scale of biogas operations [164]. In order to assess the economic viability of cassava biogas programs it will be necessary to consider the different levels of biogas production:

- Individual households.
- Community operated plants.
- Large-scale in-house farming operations, and
- Industrial plants [164].

In each of these cases, the profitability of the biogas program depends on the input (biomass, pesticides, fertilizers and transport fuels) and output (biogas, digestate and kilowatts per hour of electricity) costs. For an individual household, the profit may take 2–5 years to realize while for larger scale enterprises it may take longer, sometimes up to ten years. Some of the typically encountered input costs are related to transport fuels and fertilizers or feedstock depending on the type of operation. Again, cassava crop production requires little or no fertilizer input and biomass for biogas production can be harvested any time of the year. Cassava biogas technology is not limited by geographical location and can be locally built and operated. Consequently, it is not subject to exchange rate fluctuations [4,165].

7. Conclusions

In conclusion, this review highlights that there is a potential to use cassava biomass as a bioenergy crop, in particular for biogas. Biogas production is an old and mature technology; however, there is still room for improvement in order to overcome the existing shortcomings. Some of the shortcomings include: (a) limitations posed by the current bioreactor designs; (b) process control still relies on in- and output data; (c) the role of microbial population dynamics is still not sufficiently understood [113,115,113,109].

For sustainable cassava biogas production in Africa, rural production should first be prioritised and regulated by the national governments. Export should only be considered when the rural production has peaked. An unregulated biogas industry as it stands at the moment in Africa will harm its future development and all the multi-benefits to the rural poor and national economy will be lost.

The South African Biofuels industrial strategy in 2007 proposed a 2% penetration level of liquid biofuels or 400 million litres per annum, in the national fuel supply by 2013. It proposed the use of sugar cane and sugar beet for bioethanol, sunflower, canola and soybeans for biodiesel and excluded maize and Jatropha based on food security concerns. Surprisingly there was no mention of biogas in the 29 page document. Whether this was a deliberate omission or the shortage of skilled anaerobic digestion experts during the compilation of the document is not very clear. It did made room for adoption of new crops for bioenergy if the advantages could be proved. This review proposes cassava as that alternative crop meeting the set requirements.

Current limitations that can negatively affect the development of bioenergy as a whole in South Africa are availability of water and land. Arable land is about 14% of the total land available and about 10% of this land is irrigated, consuming 60% of the national water supply. However, in most years South Africa has surplus crop production, each of which could supply sufficient bioenergy to meet 5% of national energy supply demand. As mentioned earlier, cassava water footprint is better than most crops and its adoption will not have any negative effect on water supply.

The 2007 biofuel strategy targeted 300 000 ha ($\sim$1.4%) of the 3 Mha of underutilized, high potential arable lands (14%) located in the former homelands of KwaZulu, Transkei, Bophuthatswana, Qwaqwa, Venda, etc. Utilizing a third of such land for cassava and its biomass could produce biofuels especially biogas representing 5% of the national energy usage. It is important to note that neither cassava nor its biomass is a staple food in South Africa and therefore could be used solely for starch and energy production.

8. Future research recommendations

For future research on cassava biogas we recommend a multi-disciplinary approach involving industry, Agriculture, Engineering and Science departments of our universities. This will include:

- Biogas research that utilizes waste and non-food energy crops.
- Flexible feedstock requirements.
- Combinations of different technologies.
- Use of improved feedstock varieties that will not diminish but complement food production.

Finally, biogas production from an energy crop such as cassava can really add value to the whole bioenergy chain in Africa especially in South Africa. A holistic biogas development model that takes into consideration energy, products and wastes including the environment will make it more sustainable. For this the national government should enact biogas policies and regulations that not only cater for the interest of small farmers and industry but also women by adopting cassava biomass as an alternative biogas substrate.

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